Plant nutrients: sufficiency and requirements

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INTRODUCTION

To meet the ever-increasing need for food, feed, and fiber, the production has to keep pace with the population growth. This can be achieved by enhancing the soil fertility and making crop production efficient through optimal use of plant nutrients. Assessment of the nutrient sufficiency and requirements is an integral component of research on efficient and rational use of plant nutrient inputs. The objective of this entry is to provide a concise summary of the major developments in the research on plant nutrient sufficiency and requirements. The emphasis is placed on the salient research results from recent field studies. Readers are referred to an excellent text by Black[1] for detailed discussion and summary of the past research.

BACKGROUND INFORMATION

The need for food, feed, and fiber production is ever increasing because of the continuous, rapid population growth. The need is most pressing in the developing world.[2] Apart from water shortages, soil infertility is the major constraint on the plant growth and yield in most of tropical regions. The increased crop production can be achieved through enhanced soil fertility.[1] Soil fertility can only be sustained if the nutrients removed from the soil are replenished through addition. Also, crop production needs to be made efficient through optimal use of plant nutrients. Assessment of the nutrient sufficiency and requirements is an important component of research for efficient and rational use of nutrients from external sources.

Nutrient Sufficiency

Nutrient sufficiency or critical nutrient concentration, as more commonly termed, is a relative term because an absolute sufficiency cannot be determined. Nutrient sufficiency is a measure of nutrient concentration in the plant and is determined by plant analysis. It is preferably expressed as a range of concentrations rather than a single concentration. Sufficiency of a given nutrient lies between critical deficiency value and an excess or toxic concentration. Alternatively, nutrient sufficiency is the range of concentrations for which the yield reduction and nutrient stress symptoms are not taken into account.[3] A critical deficiency concentration of a nutrient is the one that corresponds to a yield that is 10% below the maximum on the low side, and a critical toxicity concentration of a nutrient is the one that corresponds to a yield that is 10% below the maximum on the high side.[4] It is perhaps more useful to consider critical concentration as the concentration that separates plants that would respond to addition of more nutrients from those that would not respond.[5] For practical purposes, economic criterion would appear more appropriate and the critical nutrient concentration may be termed as critical economic concentration.[6]

Nutrient Requirement

Nutrient requirement is the amount of nutrient required to achieve a yield target that is normally 90% of the maximum yield obtained under optimal nutrient regime. As for nutrient sufficiency, economic considerations are equally relevant for determining the nutrient requirements of various crop plants.[1] Nutrient requirements include both external and internal nutrient requirements. External nutrient requirement is the concentration in the growing medium, usually soil, while the internal requirement is the concentration in the plant tissue at a yield target, which is normally 90% of the maximum yield.

DETERMINING NUTRIENT SUFFICIENCY AND REQUIREMENTS

Soil and plant analyses are used for determining the nutrient requirements of crops, while plant analysis is used for establishing the nutrient sufficiency under well-defined conditions of experimentation and collection of soil and plant samples. Data on nutrient sufficiency range in plant tissue of selected grain crops[7] for macronutrients are summarized in Table 1.

Since the early finding that the chemical composition of plants changes with the nutrient supplies, attempts have been made to use the elemental concentrations for evaluating nutrient requirements of crops.

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Table 1 The range of sufficiency levels of N, P, and K in plant tissue for selected grain crops

		Sufficiency range concentration (%)		
Crop growth stage	**Plant part**	**N**	**P**	**K**
Corn or maize (*Zea mays*)				
Prior to tasseling	Leaf below the whorl	3.00–3.50	0.25–0.45	2.00–2.50
Rice (*Oryza sativa* L.)				
Maximum tillering	Newest, fully developed leaf	2.80–3.60	0.10–0.18	1.20–2.40
Barley (*Hordeum vulgare* and *Hordeum distichon*)				
Emergence of head from boot	Whole tops	1.75–3.00	0.20–0.50	1.50–3.00
Sorghum (*Sorghum bicolor*)				
37–56 days after planting	Newest, fully developed leaf	3.20–4.20	0.13–0.25	2.00–3.00
Winter wheat (*Triticum aestivum*)				
Just before heading	Top two leaves	1.75–3.00	0.20–0.50	1.5–3.00
Spring wheat (*Triticum aestivum*)				
Emergence of head from boot	Whole tops	2.00–3.00	0.20–0.50	1.50–3.00

For historical developments covering the period up to 1990, the readers are referred to the excellent text entitled *Soil Fertility Evaluation and Control* by C. A. Black.[1] The more recent literature is briefly covered in this entry. Evidently, much research has been done in determining the concentrations of nutrient elements as indexes of the sufficiency of nutrient supplies for crop growth and for determining nutrient requirements.[2,7,8]

A recent book entitled *Plant Analysis Handbook* by H. A. Mills and J. B. Jones, Jr.[7] provides tables of interpretive plant analysis data for over 1000 individual horticultural, agronomic, and plantation crops. The publication provides data on sufficiency or critical concentration range for macro- and micronutrient elements for various crop plants where the deficiency, sufficiency, and toxicity concentrations have been established over a wide range of conditions in the solution culture to field. In addition, survey range and survey average values for various nutrient elements are also presented for growing conditions under which the upper and lower limits of nutrient concentrations have not been as clearly defined as in the case of sufficiency range. Survey average value refers to the nutrient level found in healthy, normal plants without the presence of visual symptoms on the foliage showing deficiency or toxicity. Another comprehensive treatise on *Plant Analysis: An Interpretation Manual* edited by Reuter and Robinson[8] is also an excellent source of information on nutrient levels for deficiency, toxicity, and sufficiency for temperate and tropical crops, pasture species, fruits, vines, nuts, vegetable crops, ornamentals, and forest plantations. The treatise discusses in detail the concepts and principles for interpreting plant analysis, describes nutrient deficiency and toxicity symptoms in the plant, apart from providing concentration ranges of nutrients covering the range from deficiency to toxicity.

The determination of nutrient sufficiency and requirements is based on the relationships with plant growth and yield. The nutrient elemental composition of the plant at optimal yield should approximate the nutrient sufficiency levels, expressed either as individual nutrient concentrations or ratios of the various nutrient elements.[1,8] Before soil and plant tests can be used for determining nutrient sufficiency and requirements, appropriate standards should be developed through field experimentation.[9] Field experiments are considered essential for calibration because standards developed under controlled conditions, e.g., greenhouse pots may not be representative of the real world situation and may not hold under field conditions. Using the primary standards developed under field conditions, the relative sufficiency and requirements of nutrients can be determined under nonexperimental conditions. Although it is generally accepted that the determination of sufficiency requirements for nutrients leads to improved prediction of yields, it is emphasized that these values depend on the growing conditions.[1]

Several equations, which are based on the response of crop yield or relative yield or growth to nutrient concentrations in soil or plant, have been proposed for determining the nutrient requirements of crops. Black[1] provides an excellent historical perspective to the developments in research on the use of soil and plant tests for determining the nutrient requirements of crops. It is evident from the discussion that while qualitative aspects of nutrient status are useful and at times, especially in the past, was considered acceptable, no generally satisfactory system of testing plants for nutrient deficiencies has emerged. This remains a major obstruction in the use of nutrient concentrations for determining requirements in a quantitative and consistent manner. The lack of consistency, however, is not entirely unexpected in view of the fact that the concentrations of various nutrient elements are determined by the total mass of the plant, which in turn is influenced by the growing conditions relative to environment, nutrient supply and interactions among various nutrient elements, and the genetics of the crop.

Soil characteristics greatly influence the use of soil tests for determining the nutrient sufficiency or critical concentration levels for various nutrient elements. For example, a recent study with grain sorghum under rainfed cropping on nearby alfisol and vertisol sites at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru (India) showed that on the vertisol site, 90% relative grain yield was obtained at 2.8 mg/kg Olsen extractable P while on the alfisol site, 90% relative grain yield was achieved at 5.0 mg/kg Olsen P.[10] These results demonstrate that a single critical limit of available P does not hold true for sorghum on the two soil types under similar agroclimatic conditions and that the critical limit is lower for the clayey vertisol with higher phosphate buffering capacity than the sandy Alfisol with lower buffering capacity.

Field study with upland rice on an Ultisol in the humid forest zone of Ivory Coast showed that the critical limit of Bray 1 P in the soil at 90% relative rice grain yield varied from 12.5 and 15.0 mg P/kg soil for the four cultivars tested. The critical or sufficiency value tended to be lower for the P-efficient rice cultivars.[11] Using plant tissue P concentration as the criterion, the critical concentration of P in the whole rice plant tops at the tillering stage, in the 90% relative grain yield, was found to be 2 g P/kg for the four rice cultivars. It was indicated that while the rice cultivars differed in the external P requirement (concentration in the growing medium), they did not differ in their internal P requirement (concentration in the plant tissue).[11,12] In these field experiments, a significant linear relationship was observed between total P uptake in the biomass and rice grain or rice straw yield.[12]

Sahrawat, Rahman and Rao[13] provided results on the calibration of plant P test for predicting sorghum grain yield under rainfed cropping of a vertisol site (Typic Haplustert) in the semi-arid zone of India. Despite variability in the rainfall received during the three years of field study, the leaf (newest, fully developed leaf at 50% flowering stage of the crop) P concentration was found to be linearly related to grain yield (r^2 varied from 0.724 to 0.993). The relationships between leaf P and sorghum yield during the three years of study were described by the following equations.

In 1987

$$\text{Grain yield(t/ha)} = 4.057 + 28.300\,\text{leaf P(\%)}r^2 = 0.993 \tag{1}$$

In 1988

$$\text{Grain yield(t/ha)} = -7.693 + 50.0085\,\text{leaf P(\%)}r^2 = 0.724 \tag{2}$$

In 1989

$$\text{Grain yield(t/ha)} = -3.414 + 21.787\,\text{leaf P(\%)}r^2 = 0.979 \tag{3}$$

The critical or the sufficiency leaf P concentration at 90% of the maximum yield was found to be about 2.5 g P/kg (Fig. 1). Phosphorus content in the grain was not significantly correlated to yield. Two important points emerged from this study: 1) linear relationship between leaf P and yield over a range of applied P; and 2) the Cate and Nelson split method[14] of graphic presentation of relationship between leaf P and relative sorghum grain yield was found to be useful and had the practical advantage in dividing the data into responsive and nonresponsive populations.[13]

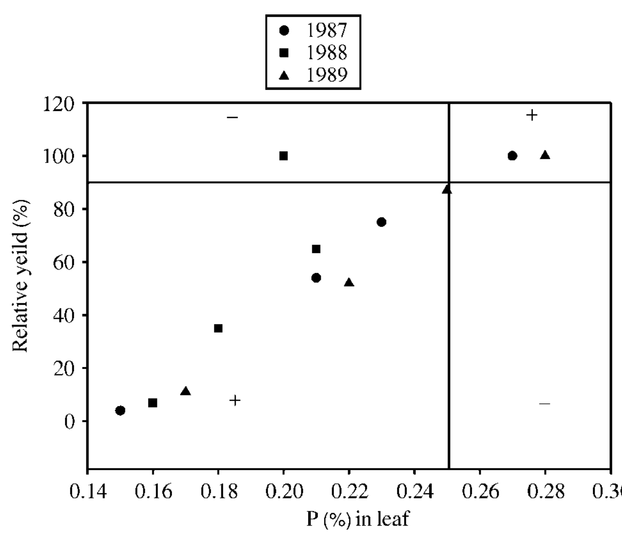

Fig. 1 Relationship between relative grain yield and P content in the index leaf (new, fully developed leaf) at flowering in sorghum grown on a vertisol for three years (1987–1989). Each point represents an average value of four replications. (From Ref.[13].)

SIMPLE MODELS FOR DETERMINING NUTRIENT REQUIREMENTS

Sahrawat[15] evaluated two methods for determining the fertilizer phosphorus requirement (FPR) of sorghum. The first method used a simple method based on P uptake[16,17] using the equation

$$\mathrm{FPR} = (U_p - U_0)/\mathrm{PRF}$$

where Up is P uptake at a given yield, U_0 is P uptake from unfertilized soil, and PRF is the P recovery fraction of applied P. The parameters U_0, Up, and PRF were determined in a three-year field experiment with sorghum grown on a calcareous vertisol site under rainfed conditions. The second method, proposed by the author, was based on the P applied, P uptake, and grain yield relationships. First, P uptake at a given sorghum yield was determined from the relationship between total P uptake and grain yield. The amount of fertilizer P applied for the given P uptake and grain yield was then determined from the relationship between P applied and P uptake. Based on three years results, it was found that the fertilizer P applied and total P uptake by sorghum were significantly and linearly related, which is described by regression Eqs. (4) and (5)

$$\text{P uptake(kg/ha)} = 1.67 + 0.200 \text{ P applied (kg/ha)} \quad (r^2 = 0.97; n = 12) \qquad (4)$$

Total P uptake by the crop in turn, was closely linearly related to sorghum grain yield, and described by the following regression equation

$$\text{P uptake(kg/ha)} = 0.51 + 2.62 \text{ grain yield (t/ha)} \quad (r^2 = 0.95) \qquad (5)$$

There was a close agreement between the observed values of FPR and the predicted values determined by the two methods. These results suggested that the simple models based on P uptake could be utilized for determining the nutrient requirements of crops.

Evaluation of the two methods described, for determining the fertilizer P requirements of upland rice cultivars grown for two seasons (1992–1993) under a range of applied P on an ultisol site in the humid forest zone of Ivory Coast, showed that there was a good agreement between the observed values of FPR and the predicted values of FPR that were determined by the two methods. This indicates the usefulness of these simple methods based on P uptake for determining the P requirements of crops.[18] As observed for sorghum, fertilizer P applied and P uptake and grain yield and P uptake by four upland rice cultivars were significantly and linearly related. Overall, the results obtained with upland rice on an ultisol site in the humid forest zone and sorghum on a vertisol site in the semi-arid tropical zone indicate a wide applicability of these simple models for determining P requirements of crops and merit further evaluation.

It was further indicated that using the Cate and Nelson split method,[14,19] of graphic presentation of relationships between P applied and relative rice grain yield or between P uptake and relative yield provided a simple procedure for determining the P requirement of rice.[18]

The author's unpublished results showed that a significant and linear relationship exists between fertilizer N (as urea) and N uptake, and between grain yield and N uptake for lowland rice cultivars grown under irrigated conditions on Alfisols in central Ivory Coast. It was further indicated that these relationships could be used for determining the N requirements of lowland rice cultivars.

In a recent study, Pathak et al.[20] used the Quantitative Evaluation of Fertility of Tropical Soils (QUEFTS) model[21] for estimation of N, P, and K requirements and fertilizer recommendations for targeted yields of wheat in India. The model considers the interactions of N, P, and K, and climate adjusted potential yield region-wise in the country. Published data from field experiments conducted between 1970 and 1998 across the wheat-growing environments of India, covering a wide range of soils and climatic conditions, were used to capture the environmental variability effects on wheat yield. The relationships between soil's inherent N supply and soil organic C, P supply and Olsen extractable P in soil, and K supply and ammonium acetate extractable soil K were established. The results showed that required N, P, and K accumulation in the plant biomass for 1 t grain yield was 23.1, 3.5, and 28.5 kg, respectively. The observed yields of wheat with different amounts of N, P, and K were in agreement with the values predicted by the model, indicating that the QUEFTS model can be used for determining nutrient requirements and fertilizer recommendations for wheat production.

CONCLUSIONS

The research on determining the nutrient sufficiency and nutrient requirements of plants is a prerequisite for the efficient use of purchased inputs of nutrients and for making the overall agricultural production more efficient through optimal use of plant nutrients. However, there have been problems in consistency of the results, which are greatly influenced by growing conditions and complex interactions among environmental, cultural, and genetic conditions.[1] Despite these limitations, the knowledge of nutrient sufficiency and requirement is helpful in improving the prediction of plant growth and yield. A combination of soil and plant tests may be more effective in determining the nutrient sufficiency and requirements of crops. While soil tests are effective in determining the long-term nutrient requirement of crops, plant tests are necessary to diagnose and correct the nutrient deficiency of the current crops.[13,22,23] There is need for future research to strengthen the use of models for determining nutrient requirements and fertilizer recommendations for crop production, as field experimentation is expensive and at times not practical.

ARTICLES OF FURTHER INTEREST

Boron and Molybdenum, p. 188.
Calcium, p. 198.
Copper, p. 345.
Fertility Evaluation Systems, p. 670.
Magnesium, p. 1045.
Nutrient Deficiency and Toxicity Symptoms, p. 1144.
Potassium, p. 1354.
Sulfur, p. 1717.
Sustainability and Integrated Nutrient Management, p. 1732.
Testing, p. 1755.

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